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The research under this grant concentrated in three major areas; Object representation, feature extraction and matching and recognition control strategies.

Advances were made in all three areas: Using Aspect Graphs as the representation of objects scheme it was possible to efficiently match orthographic projection of objects as well as perspective projections. Also efficient feature extracting algorithms were developed using Fourier Descriptors. Non linear optimization techniques were used for recognition.

Eight publications resulted from this research.

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This document constitutes the final report for the research contract AFOSR 87-0316, resulting from the proposal entitled *A Viewing Spheres Approach to a Robotic Vision System*, and funded for the period 7-15-87 through 7-14-88.

The following publications have resulted from the research carried out under this contract:

1. Stewman, J.H. and Bowyer, K. *Aspect Graphs for Planar-Face Convex Objects*, Proceedings of the IEEE Workshop on Computer Vision (December 1987), 123-130.

2. Stewman, J., Stark, L., and Bowyer, K. *Restructuring Aspect Graphs Into Aspect- and Cell-Equivalence Classes for Use In Computer Vision*, presented at Graph Theoretic Concepts in Computer Science (WG '87), Staffelstein, West Germany (June 1987), refereed version to appear in a volume in Springer-Verlag Lecture Notes in Computer Science Series.

3. Stewman, J., and Bowyer, K. *Direct Construction of the Aspect Graph of Convex Polyhedra*, C.S.&E. Technical Report 88-007 (January 1988), University of South Florida. Submitted to CVGIP.

4. Stewman, J.H., and Bowyer, K. *An Aspect Graph Object Representation for Computer Vision*, Proceedings of the Florida AI Research Symposium (May 1988), 41-45.

5. Eggert, D. and Bowyer, K. *Matching the Complete Edge Structure of the 2-D Projection of an Object Using Fourier Descriptors*, Proceedings of the Florida AI Research Symposium (May 1988), 223-227.

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8. Bowyer, L., Stewman, J., Stark, L., and Eggert, D. *ERRORS-2: A 3-D Object Recognition System Using Aspect Graphs*, to appear in Proceedings of the International Conference on Pattern Recognition (October 1988).

Copies of these publications may be obtained by contacting the principal investigator. A preprint of *ERRORS-2: A 3-D Object Recognition System Using Aspect Graphs*, which gives an overview of the research conducted under this contract, appears as the body of this final report.

ERRORS-2: A 3-D Object Recognition System Using Aspect Graphs [1]

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Abstract.

This report describes a prototype 3-D object recognition system composed of three major sections; 1) an object representation module, 2) a feature extraction and matching module, and 3) a recognition control strategy module. The object representation module uses an implementation of a newly developed algorithm for the construction of perspective projection aspect graphs of convex polyhedra. The feature extraction and matching module implements a new method of using Fourier Descriptors to characterize the complete 2-D projection of an object. The recognition control strategy module uses the aspect graph object representation to control the application of a constrained optimization algorithm. The system is implemented in C on a SUN workstation, and some simple recognition experiments have been carried out to demonstrate the validity of the overall concept. The limitations of the system suggest several important avenues for future research.

Keywords: Three dimensional, Two dimensional. (SDW)

1. Introduction

The long-term goal of our research group (dubbed "ERRORS" for "Environment for Related Research in Object Recognition Systems") is to construct a 3-D object recognition system with a useful level of practical competence. For our current work, 3-D object recognition means recognizing the identity of the object and having some estimate of its parameters of location and orientation. The design of a 3-D object recognition system must generally take into account three interrelated concerns; 1) object representation, 2) feature extraction and matching, and 3) recognition control strategy. Accordingly, our current system is structured into three major modules, reflecting the combined work of several people. The basic results underlying each of these modules are outlined in sections 2, 3 and 4. Section 5 describes the results of some experiments which demonstrate the basic capabilities of the system. Section 6 outlines the limitations of the current system, and suggests areas of further research to produce a new system of greater competence.

[1] This work is supported by Air Force Office of Scientific Research grant AFOSR-87-0316.

2. Object Representation Using Aspect Graphs

Traditional approaches to 3-D object recognition can be characterized as either view-dependent or view-independent, according to whether the object representation used during recognition is some set of standard 2-D views or a true 3-D model, respectively [1, 4]. The aspect graph concept, originally introduced by Koenderink and van Doorn [12] as a possible mechanism involved in human vision, can be thought of as a hybrid representation which combines a true 3-D model with an enumeration of all the fundamentally different views of the object. The potential power of the aspect graph concept has been quickly and widely recognized in computer vision, and a number of researchers have recently described algorithms for creating representations related to the aspect graph.

One major distinction between the different representations which have been proposed is whether or not they depend on the assumption of orthographic projection. If orthographic projection is assumed, then the "cell" of viewing space associated with a node of the aspect graph corresponds to a surface area on the Gaussian sphere [2, 3, 7-9, 11, 13, 15, 17]. The important distinction with regard to our work is that this type of *orthographic projection aspect graph* only captures changes in the aspect which are due to changes in viewing orientation. Thus, it cannot be used for recognition which includes estimating the parameters of translation.

Relatively less work has been done on algorithms for constructing the *perspective projection aspect graph*. The first algorithm for constructing the perspective projection aspect graph of 3-D objects was developed by Stewman and Bowyer [21], and is applicable only to convex polyhedra with trihedral vertices. This algorithm was subsequently extended to handle general convex polyhedra [22]. Complete details of the algorithm and an analysis of the time and space complexity appear in [23]. We have since learned of related work by two other researchers; Watts [26] has described an algorithm for constructing the aspect graph of convex polyhedra using a *sweep-plane* paradigm, and Edelsbrunner [5] has described an algorithm for constructing the *geometric incidence lattice* representing the *arrangement* of planes in space. The geometric incidence lattice is a different and more abstract entity than the aspect graph, but the algorithm could easily be extended to create the aspect graph.

Our algorithm to create the aspect graph begins by finding all the lines and points of intersection between the planes in which the faces of the object lie. The algorithm then uses all these points of intersection, plus additional points on the infinite extensions of each line, to isolate groups of points on the boundary of individual 3-D "viewing cell" volumes. Finally, the algorithm constructs an explicit aspect graph structure and writes the resulting representation to disk. An example aspect graph for one of the objects used in our experiments is shown in Figure 1. The user interface to the implemented algorithm is described in [24]. The important elements of the representation for our purposes here are that each node of the aspect graph is attributed with 1) a definition of the corresponding 3-D cell of viewing space, 2) a definition of which faces are visible from viewpoints in that cell, and 3) the coordinates of a "central viewpoint" in the cell. In addition, the aspect graph is arranged by levels, where each node in a given level has the same number of visible faces.

3. Feature Matching Using Fourier Descriptors

Fourier Descriptors (FDs) have been used for some time in both 2-D and 3-D object recognition. Several researchers have applied the technique for 3-D object recognition by using the FDs of the boundary outline of the 2-D projection of the 3-D object [16, 25]. While this technique has had some success, there are clearly some objects which could not be distinguished by only the boundary outlines of their 2-D projections. Eggert and Bowyer [6] have developed a method of using FDs to describe the shape of the internal detail of the 2-D projection of an object as well as its boundary outline. The feature extraction and matching module of our current system uses this method.

The feature matching module undergoes an initialization step which involves processing the original image. The module extracts the line drawing of the object in the image, selects a unique subset of all the possible circuits in the line drawing, and calculates the FDs for each circuit in this unique subset. For convex polyhedra, each circuit in the chosen subset corresponds to a face of the object. Thus this feature extraction and matching strategy seems particularly appropriate to the class of objects for which we are currently able to create the aspect graph representation.

On subsequent invocations of the feature extraction and matching module, the parameters of translation and orientation of an object model are given as input. The module calculates a perspective projection line drawing of the object model from the visible faces attributed to the aspect graph node, extracts the unique set of circuits from the line drawing, calculates the FDs for each circuit in the unique set, pairs up the circuits from this line drawing with those from the original image, and determines the best match for the set of circuits. The algorithm reports a figure of merit for the match, along with the (2-D) rotation and scale used to obtain the best match. The figure of merit for the match is the sum of the squares of the differences of the FDs for each of the circuit pairs.

4. Recognition Using Nonlinear Optimization

Several previous researchers have applied nonlinear optimization as a control strategy for 3-D object recognition [10, 14, 25]. The fundamental problems encountered are 1) how to choose starting parameter estimates, and 2) how to know when the global minimum has been found. Stark and Bowyer [18] suggested a method of using the aspect graph representation to control the application of nonlinear optimization in a way that avoids these problems. The basic idea behind this method is fairly simple. Assume that we have a database in which objects are represented by perspective projection aspect graphs, and are given an image in which an unknown object appears at an unknown orientation and translation. Since each node corresponds to a different aspect of an object and the cell of space from which that aspect is seen, we can generate a separate optimization solution for each node in the database. Thus, for each node, we get the minimum found within the corresponding viewing cell. We then select the minimum across all nodes as the recognized view of the unknown object in the image.

Stark, Eggert and Bowyer describe the specific implementation of this general approach used in our current system [19]. Since the aspect graphs are arranged by levels corresponding to the number of visible faces, only nodes whose number of visible faces matches the number of circuits found in the original image are considered as candidates by the recognition process. For each candidate node, the optimization algorithm proceeds as follows. First, initial estimates of the parameters of translation [X, Y, Z] and rotation [R_x, R_y, R_z] are constructed. The feature matching module is invoked to create a projected line drawing, extract and match features, and return the figure of merit for the match as the value of the objective function, as well as the rotation and scale used in the 2-D match. The 2-D rotation and scale values are used immediately to update the Z and R_z viewpoint parameter estimates. Then finite differences are calculated for X, Y, R_x, and R_y, and step values in these four parameters are derived using damped least squares. This results in a complete set of parameters for a new viewpoint.

If the new viewpoint is within the viewing cell, and the objective function decreases at the new viewpoint, then the Z and R_z viewpoint parameter estimates are updated according to the new 2-D rotation and scale values returned from the last match, new finite differences are calculated, and new step values determined for X, Y, R_x, and R_y. If the value of the objective function goes below a zero tolerance, then the process terminates. If the new viewpoint would be outside the bounds of the cell, or if the objective function would increase at the new viewpoint, then the damping factor is increased and new step values for X, Y, R_x, and

R_y are calculated.

5. Performance of the Current System

In order to assess the effectiveness of this approach to 3-D object recognition, several simulated recognition experiments were carried out [19]. One of experiments attempts to assess how well the approach does at recognizing the correct object by selecting the lowest objective function value across a set of candidate aspects. For this experiment, we randomly generated 25 simulated viewpoints for each of 5 different three-face aspects taken from 4 different object models (see Figures 1 and 2). For each of the simulated viewpoints, we started up the optimization process for each of the 5 aspects. Thus, for each simulated viewpoint, we have one optimization result found in the correct viewing cell and 4 results found in incorrect viewing cells. The results are summarized in Table 1. Three of the aspects matched correctly in all 25 trials. One aspect matched correctly in 24 out of 25 trials; one three-face view of the cube was mistaken for a three-face view of the rectangular block. The remaining aspect matched correctly in 23 out of 25 trials; twice a three-face view of the rectangular block was mistaken for a three-face view of the truncated wedge. The two incorrect matches for the truncated wedge occur when the outline of the third face, which is the only significant difference between the two aspects, has collapsed to nearly a single line. Thus, these would always be difficult viewpoints to handle correctly. The other incorrect match appears to be an anomaly where the method simply results in an incorrect choice for recognition.

6. Summary and Suggestions for Future Work

We have developed an algorithm for the construction of perspective projection aspect graphs of convex polyhedra, developed a new method of using Fourier Descriptors to characterize the complete line drawing of such objects, and formulated a methodology which uses the aspect graph to apply optimization techniques for recognition. Our current prototype system pulls these results together to provide a demonstration of the potential of aspect graph based 3-D object recognition. Much more work must be done in several areas before a system with a truly interesting level of practical competence can be constructed.

One major line for continued research is to be able to construct the aspect graph for a larger class of objects. We are currently working on an algorithm for nonconvex polyhedra. After that, we plan to investigate an algorithm for objects defined as a CSG construction of spheres, cones, cylinders, and blocks. Ideally, this algorithm will be able to take the output of existing solid modeling systems as its input. Because the worst-case size of an aspect graph is so large, $O(N^3)$ for convex polyhedra, we are also investigating concepts of node equivalence which may be used to reduce the effective complexity [20]. We are also interested in developing strategies to choose a succession of views to recognize an object which cannot be distinguished from the information in an initial view. Lastly, we plan to investigate using different types of features, such as "non-accidental properties," to create a more robust feature matching strategy.

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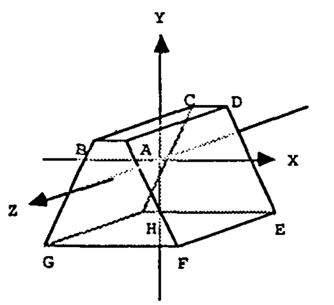
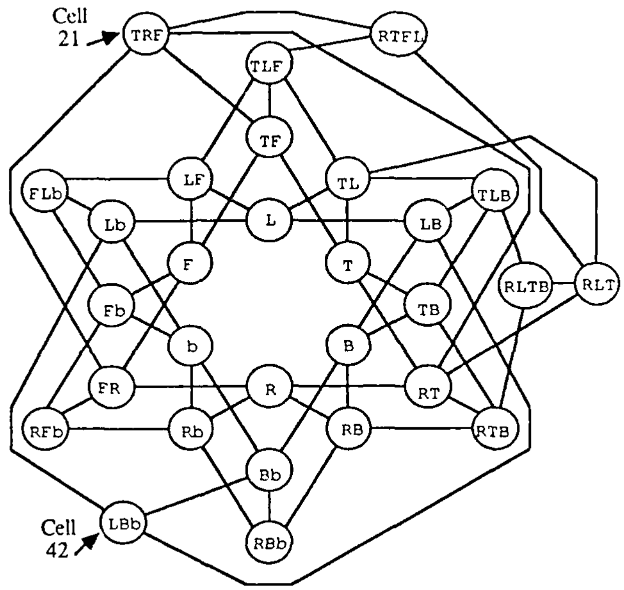
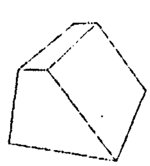


POINT	COORDINATES
A	(1/4,1/2,1)
B	(-1/4,1/2,1)
C	(-1/4,1/2,-1)
D	(1/4,1/2,-1)
E	(1,-1,-1)
F	(1,-1,1)
G	(-1,-1,1)
H	(-1,-1,-1)

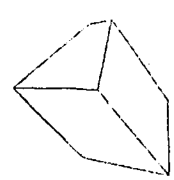
(a) Truncated wedge and corner point coordinates



(b) Aspect graph for truncated wedge

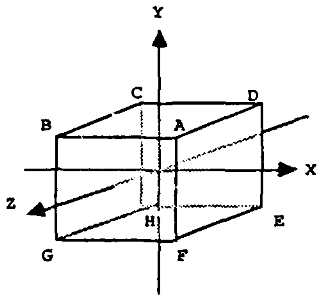


(c) Initial view from Cell 21



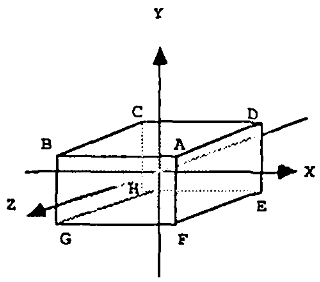
(d) Initial view from Cell 42

Figure 1 - Truncated wedge with (a) corner point coordinates, (b) aspect graph, and (c,d) initial views of two 3-face cells.



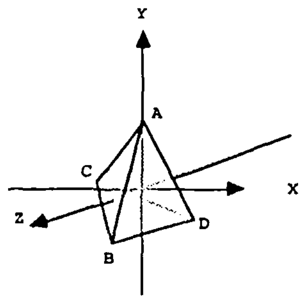
POINT	COORDINATES
A	(1,1,1)
B	(-1,1,1)
C	(-1,1,-1)
D	(1,1,-1)
E	(1,-1,-1)
F	(1,-1,1)
G	(-1,-1,1)
H	(-1,-1,-1)

(a) Cube and corner point coordinates. Initial view from Cell 21 (below).



POINT	COORDINATES
A	(3/4,7/8,1)
B	(-3/4,7/8,1)
C	(-3/4,7/8,-1)
D	(3/4,7/8,-1)
E	(3/4,-7/8,-1)
F	(3/4,-7/8,1)
G	(-3/4,-7/8,1)
H	(-3/4,-7/8,-1)

(b) Rectangle and corner point coordinates. Initial view from Cell 21 (below).



POINT	COORDINATES
A	(0,0.633,0)
B	(0,-1,1.1547)
C	(-1,-1,-.57735)
D	(1,-1,-.57735)

(c) Tetrahedron and corner point coordinates. Initial view from Cell 11 (below).

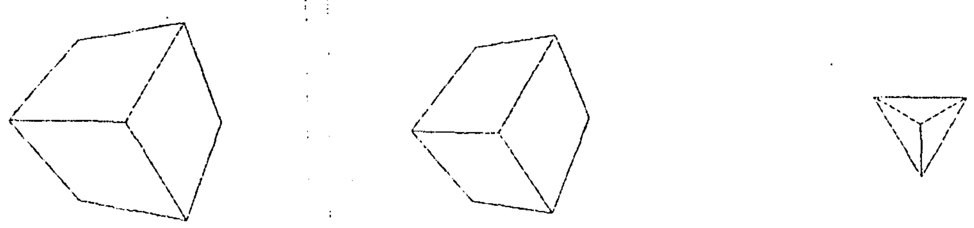


Figure 2 - Additional test objects with corner point coordinates and initial view of 3-face cells used in matching process.

Table 1 - Result of match across object model base.

Simulated image of ... \ Matched to...	Cell 21 Wedge	Cell 42 Wedge	Cell 21 Cube	Cell 21 Rect.	Cell 11 Tetrahedron
Cell 21 Wedge	23			2	
Cell 42 Wedge		25			
Cell 21 Cube			25		
Cell 21 Rect.			1	24	
Cell 11 Tetrahedron					25

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